Chapter 14

THE IMPACTS OF CLIMATE CHANGE ON FORESTRY

LINDA A JOYCE

Abstract. The quantitative analysis of the impact of future climate change on forests and forestry began in the 1980s, motivated by research in the atmospheric sciences and concerns about the potential impacts of climate change on forest ecosystems. These analyses suggested that forest ecosystems would be seriously impacted by climate change, with consequent impacts on the forest sector. It was not until the mid-1990s that the ecological and the economic impacts were first modeled together at the national scale. The RPA Timber Assessment was the first national timber assessment model to include climate change scenarios impacting forest productivity and the forest sector. The modeling treatment of climate change included exogenous analyses of climate change impact on ecosystem productivity under various climate change scenarios and linked such analyses to the forest sector modeling system. These analyses and the work that built on this approach suggest the importance of integrating ecological dynamics with the economic in the assessment of climate change on forests.

Keywords: ecosystem productivity, biogeochemical, biogeographical, producer and consumer welfare

14.1 INTRODUCTION

The quantitative analysis of the impact of future climate change on forests and forestry began in the 1980s, motivated by research in the atmospheric sciences (National Research Council 1983). Initial reports (Peters 1987; Shands and Hoffman 1987; Smith and Tirpak 1988) suggested that forest ecosystems would be seriously impacted by climate change, with consequent impacts on the forest sector. These early ecological analyses focused on individual regions or individual

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tree species, without considering the potential for new tree species to migrate or the impact of market dynamics on the ecological responses. The first effort to link the ecological impacts with the economic was a study by Binkley (1988) where a simple regression approach of the ecological impact was imposed on a multiregion model of boreal forest products trade. Limitations included the simplistic forest growth model and a focus on only the boreal region. In the late 1980s, TAMM was used to value acidic deposition or air pollution effects for US forests (Haynes and Kaiser 1990). These effects were modeled as reductions in potential yields that eventually reduced timber harvests, producing modest economic effects. Hodges et al. (1989) used ecological analyses by others to estimate the impact of climate change on the forest sector of the Southeastern US, but did not consider price or trade effects. This early work suggested the importance and challenges of taking an integrated approach to climate change analyses (Binkley and van Kooten 1994).

This chapter describes the evolution of analytical tools used to quantify impacts of climate change on forest productivity, forest diversity, and the supply and demand for wood products. Across the different analytical approaches and climate scenarios currently used, the conclusions are similar. The forest sector is remarkably adaptable in the face of these potential climate changes. Climate change is likely to alter forest productivity with potential increases in the near future. The regional impacts differ greatly. Increases in the timber inventory lead eventually to lower prices as increases in timber harvests enter the market. Although producers respond with management options to the new conditions, the lower prices result in declines in producer welfare, but consumers generally gain. These results hold when there is large-scale dieback (extensive forest mortality) and there are adaptive responses by producers (salvage harvest, planting appropriate species). Research to continue to enhance these assessments is also reviewed.

14.2 THE RPA–FOREST SERVICE POLICY ANALYSIS

The RPA legislation directed the Secretary of Agriculture to prepare a Renewable Resources Assessment in 1975 and starting in 1979, a decadal update. The assessment was to include "an analysis of present and anticipated uses, demand for, and supply of the renewable

resources, with consideration of the international resource situation, and an emphasis of pertinent supply, demand, and price relationships trends." Since 1974, the Forest Service has led this assessment effort with four national assessments and two updates which have reviewed the current and likely future condition of forest and range resources including wildlife, water, timber, recreation, range forage, and minerals (USDA FS 1989, 1994, 2000, 2007).

These assessments typically include: (1) a description of the current status of the resource; (2) a projection of supply of and demand for resource outputs; (3) social, economic, and environmental implications of the projections; and (4) management opportunities to improve the resource situation. The results of the RPA Resource Assessment are used in formulating future renewable resource management programs within the Forest Service. The structure of these ongoing assessments provides a mechanism by which current scientific information can also be synthesized periodically to address policy questions (Joyce 2003).

14.2.1 Climate change analyses within the RPA Resource Assessments

The 1990 Food, Agriculture, Conservation, and Trade Act amended the 1974 RPA legislation to require the Forest Service to assess the impact of climate change on renewable forests and rangelands resources, and to identify the rural and urban forestry opportunities to mitigate the buildup of atmospheric carbon dioxide. These analyses were to be included as part of subsequent RPA Resource Assessments.

Since this amendment, the RPA Resource Assessments have included an analysis on the vulnerability of US ecosystems to changes in climate and the potential impact on the social and economic systems from changes in climate. The 1989 RPA Climate Change Assessment reviewed the current scientific understanding of the potential effects of global climate change on forests (Joyce et al. 1990). The 1993 RPA Timber Assessment used an integrated modeling framework to analyze the impact of climate change on ecosystem productivity, timber supply and demand, and carbon storage (Joyce 1995; Joyce et al. 1995). The 2000 Climate Change Assessment described the state of the art in assessing the impacts of climate change on forest productivity, ecosystems distributional shifts, the forestry sector, and carbon sequestration opportunities (Joyce and Birdsey 2000). The 2005 RPA Timber Assessment incorporated the transient analysis of climate change into the forest sector modeling effort (Haynes et al. 2007).

Rural and urban forestry opportunities to mitigate the buildup of atmospheric carbon dioxide have been jointly addressed by RPA-related research efforts and the Forest Service Global Change Research Program (Joyce and Birdsey 2000). Forest inventory data have been used to estimate historical carbon stocks and fluxes (Heath and Birdsey 1993). The development and improvements of a carbon accounting model (Plantinga and Birdsey 1993) have led to opportunities to explore management and policy options for increasing the role of forest lands in sequestering carbon emissions (Smith and Heath 2004).

14.3 ENHANCING THE TIMBER POLICY MODELING FRAMEWORK FOR CLIMATE CHANGE ANALYSES IN THE 1980s

To develop forest policy actions to meet the challenges and opportunities of climate change, an integrated assessment is needed where climate information, forest productivity, forest management, and the demand for forest products is considered holistically. There are three main approaches to integrated assessments: (1) the vertical assessment, where integration occurs through the chain of effects from changes in atmospheric composition and climate to changes in biophysical systems to socioeconomic consequences; (2) the horizontal assessment, which emphasizes the interactions among systems, sectors, and activities; and (3) the time assessment, where trends in society are projected over the transient path of the projected climate (Watson et al. 1998). Each of these approaches offers important insight into questions surrounding the impact of climate change and climate variability on the forest environment and economy. The vertical approach was taken to incorporate climate change into the RPA Resource Assessment, with consideration of the temporal dynamics (Joyce 1995; Joyce and Birdsey 2000).

14.3.1 Modeling forest growth and yield in the forest sector model

As described in Chapters 2 and 6, the Timber Assessment Projection System (hereafter Assessment System) has been used to describe forest sector dynamics over a 50-year planning period for strategic planning within the RPA Timber Assessments. The Assessment System

was designed to provide long-term projections of price, consumption, and production trends in both the stumpage and the product markets and to simulate alternative forest policies and programs in the US forest sector (Haynes 1990). Within the Assessment System, ATLAS provides a 50-year projection of growth and harvest on US timberland. For the 1993 RPA Timber Assessment, the Assessment System structure was essentially as shown in Figure 2-1.

The timber inventory projection system, ATLAS, models timber inventory changes at subregional, regional, and national scales, through changes in growth, area changes, harvest, and the effects of timber management (see Chap. 6 for details). Timber inventory is classified by region, ownership, timber management type, management intensity, and age class. ATLAS can simulate growth and removal processes across all age classes, account for partial harvest, commercial thinning, final harvest, and the harvest of acres removed from timberland. The projection mechanism in ATLAS moves timber cells (finest division of the inventory classification scheme) along age-based yield trajectories. The yield tables, density change coefficients, and stocking density coefficients required for growth models within ATLAS are derived from inventory plot data and other research studies.

The model of forest growth in ATLAS builds on the traditional approaches used by silviculturists to estimate growth and yield in forest stands, referred to as allometric models, or alternatively labeled "forest growth models" (Dale et al. 1985). These models predict tree growth based on regressions with simple dependent variables that generally involve age, stand density, and site index. Allometric models reliably estimate merchantable timber yield for the range of the data used to calibrate the models, but they do not perform well when extrapolated outside of the calibration range (Dale et al. 1985). These models are not typically driven by climatic variability. With respect to climate, the assumption within these models is that historical patterns of climate will continue and the relationship between environmental variables such as temperature and precipitation, and growth remains unchanged. Without an explicit link to climate, they cannot be used to predict the response of forest growth to changes in climate (Agren et al. 1991). Similarly ATLAS does not identify specifically the impact of environmental factors such as climate on timber growth and yield (Mills and Kincaid 1992). The omission necessitates a link between the timber inventory models and the ecological models which have incorporated environmental drivers.

14.3.2 Modeling the ecological dynamics of forests

In the 1980s, approaches to modeling the ecological response of plants and forests to climatic change varied by ecological discipline and may or may not have had management as an explicit component of the modeling framework. Physiologically based plant models focus on biochemical reactions within individual plants and their responses to climate and elevated atmospheric carbon dioxide. At that time, the challenge to these models was scaling the processes up to a mix of species or a forest stand. Plant establishment, growth, seed production, and death are simulated in population–community models at larger spatial scales than the physiologically based models. Gap-phase models[1] predict future forest species composition for an area of the forest ("gap") where a disturbance has resulted in an opening of the closed forest canopy. Individual species compete for light, water, and nutrients with the result of a shift to species better adapted to the changing environment. A major uncertainty in these models was the rate of species dispersal into a region and the lack of explicit dispersal mechanisms (US EPA 1988). Regional and global biogeographical models had been developed at the time by using the coincidence of climate and vegetation zones (correlation) to describe the future distribution of plant communities under a changing climate. These climate–envelope models assume an equilibrium relationship between climate and plant distribution. In the 1980s and 1990s, models were developed within the rapidly expanding field of ecosystem ecology that focused on the dynamics of ecosystem productivity through the biogeochemical processes of fixation, allocation, and decomposition of carbon and the cycles of nitrogen, phosphorus and other elements. These models were beginning to use spatially referenced information on climate, elevation, soils, vegetation and hydrology to make monthly estimates of ecosystem productivity at continental spatial scales (Schimel et al. 1990; Burke et al. 1991; Raich et al. 1991; Melillo et al. 1993).

[1] Gap models quantify the establishment, growth and mortality of individual trees by taking into account the stochasticity both of weather and of demographic processes on small patches of land (gaps resulting from fine-scale disturbance), scaled to the maximum size achievable by a single individual. (After Bugmann et al. 1996.)

14.3.3 Linking climate scenarios to ecological models and forest sector models: a modeling framework

Like most forest policy models, the Assessment System assumes that the future climate would follow historical climate patterns and that changes in timber production and land use are an outgrowth of these historical patterns (Joyce et al. 1990). The rich details of the forest sector dynamics are modeled without explicit mention of environmental factors. Ecological models describe the influence of climate and other environmental factors on productivity without the explicit development of the merchantable wood component of forest biomass. A way to pass information between climate models, ecological models, and the forest sector model was needed.

The spatial scale of the forest sector (stumpage and product markets) is both national and regional and requires a careful pairing with appropriately scaled ecological models. Forestry policy models, such as the Assessment System, operate at the national scale, a spatial scale that ecologists in the late 1980s were just beginning to use in ecological models. As climate change was likely to take ecosystems outside of the historical range of natural variability, the early global productivity models, typically regression-based, appeared to offer limited analyses of this uncertain future (McGuire et al. 1993), when compared to ecosystem models that quantified the biogeochemical process critical to forest productivity, such as environmental and nutrient influences on carbon fixation, allocation and decomposition.

Information flows between climate models and ecological models consisted of "deltas," the relative changes in climatic factors, which were computed in the climate models and then imposed on the ecological models. This approach was used to construct a modeling framework for assessing climate change in the forest sector (Figure 14-1). The structure of the Assessment System modeling framework was modified to add information developed exogenously by climate models and biogeochemical models that would be used to modify the growth coefficients in ATLAS. The biogeochemical model chosen to link to this modeling framework was the Terrestrial Ecosystem Model (TEM) model (McGuire et al. 1992, 1993; Melillo et al. 1993). TEM is a process-based model which uses spatially referenced data on climate, soils, and vegetation to estimate net primary productivity (NPP) as affected by carbon and nitrogen cycling and environmental factors. The spatial scale of the TEM modeling effort was continental, where

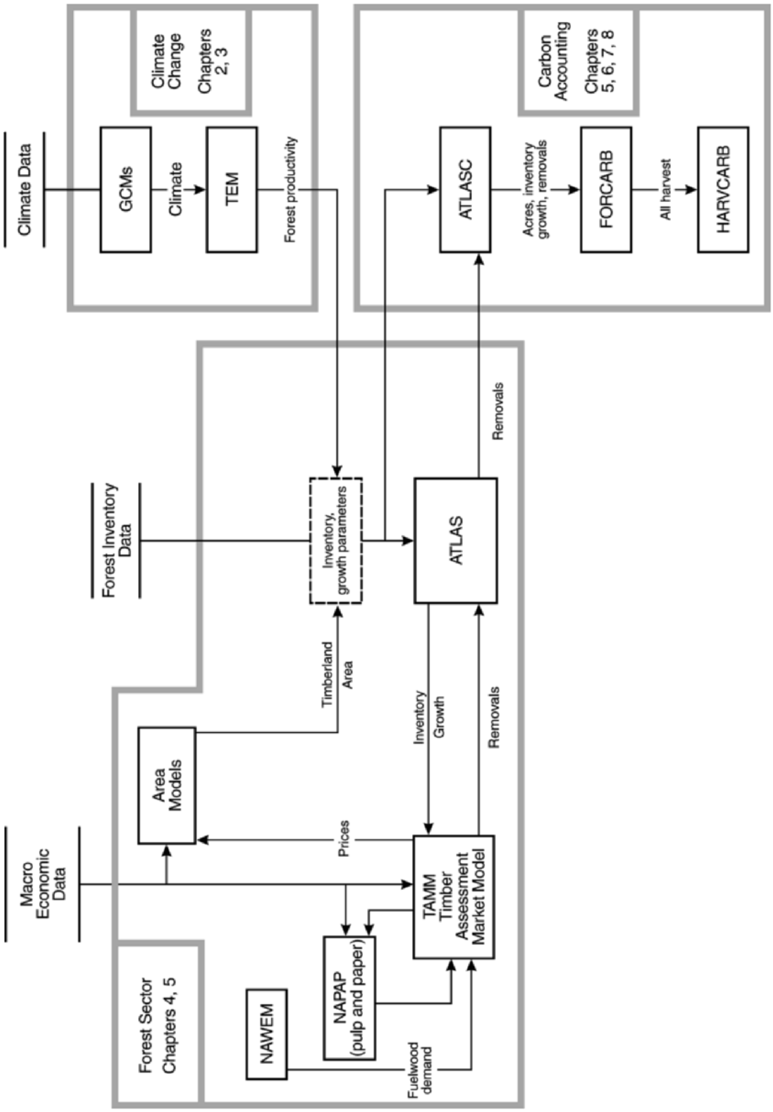

Figure 14-1. RPA climate change modeling framework used for the climate change assessments. (Chapter numbers refer to Joyce and Birdsey 2000.)

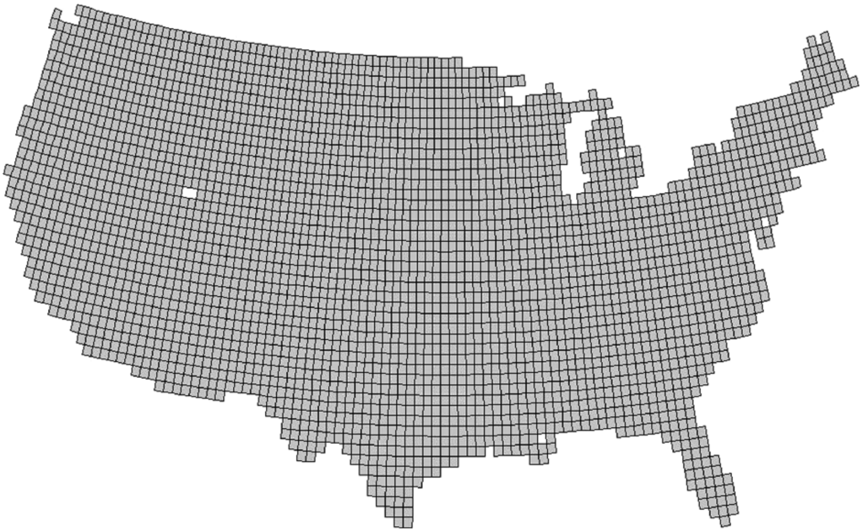

Figure 14-2. Map of 0.5 degree latitude × 0.5 degree longitude grids representing the spatial scale for analysis within the ecological models. Spatially referenced data for soils, vegetation, and climate was associated with each grid cell and net primary productivity as affected by carbon and nitrogen cycling and environmental factors was estimated for each grid cell.

ecosystem dynamics were modeled within 0.5 degree longitude by 0.5 degree latitude grid cells (Figure 14-2). Ecosystem types used by TEM include boreal forest, boreal forest wetlands, temperature deciduous, temperate mixed, temperate coniferous, temperate forest wetlands, and temperate broadleaf evergreen forest.

14.4 PROJECTING CLIMATE CHANGE, ECOLOGICAL IMPACTS, AND FOREST SECTOR IMPACTS: THE STATIC ANALYSIS IN THE 1993 RPA TIMBER ASSESSMENT

Climate scenarios from four general circulation models (GCM) were used to examine the impact of climate change on forest productivity: Oregon State University (OSU), Goddard Institute of Space Sciences, and two versions of the Geophysical Fluid Dynamics Lab model (Joyce 1995). These global models provided equilibrium climates under elevated atmospheric carbon dioxide concentrations at a coarse spatial

resolution. The climate models were run for the current climate (1990) with current levels of atmospheric carbon dioxide (estimated at 355 parts per million [ppm]) and then for a future climate with a doubling of carbon dioxide in the atmosphere (estimated at 625 ppm), assumed to occur in approximately 2065 under the International Panel on Climate Change (IPCC) business-as-usual scenario. The four climate scenarios, interpolated to 0.5 degree longitude by 0.5 latitude spatial resolution, encompassed temperatures changes globally of 2.8–4.2°C and precipitation changes from 7.8% to 11% (Melillo et al. 1993). Climates for two points in time were then used as climatic input for TEM to project ecosystem productivity.

14.4.1 Climate change impacts on forest productivity

Because the GCMs describe the same physical processes of the atmosphere slightly differently, each model produces a different equilibrium climate, and the TEM results varied by the climate scenario and by ecosystem type (McGuire and Joyce 1995). The NPP of temperate forests in the USA increased from 8% to 27%, depending on the climate scenario. This range in changes in NPP was within the range of other analyses conducted at the time, including VEMAP (Vegetation Ecosystem Modeling and Analysis Project (1995)) where several different climate scenarios and different biogeochemical models were used to project NPP under climate change (Table 14-1). Relative to other biogeochemical models in the VEMAP study, TEM results were most responsive across all scenarios.

Are these productivity shifts from the ecological models similar to the biological potential of current US forests or to increases seen under economic opportunities fostered by timber management over a similar time frame? Vasievich and Alig (1996) identified biological opportunities to increase timber growth by 39% over the current net annual growth (without climate change). They also estimated that economic opportunities existed to increase current net annual growth by 25%. Thus, timber management could potentially enhance forest productivity to a larger degree (25–39%) than was projected in the 1993 RPA Timber Assessment for the productivity response to changes in carbon dioxide or climate (8–27%) (Joyce and Nungesser 2000).

For the 1993 RPA Timber Assessment, NPP was the ecological variable chosen to develop the change metric for the growth and yield

Table 14-1. Net primary production response to climate change and elevated carbon dioxide for different biogeochemical models

Climate scenario	Conterminous US						
	All forests NPP response			All ecosystems NPP response		Timberland in US net annual growth response	
	TEM[a]	TEM[b]	TEM[c]	Century[c]	BBGC[c]	Biological opportunities[d]	Economic opportunities[d]
				Percent			
None	—	—	—	—	—	39	25
GISS[e]	27	—	—	—	—	—	—
GFDL-1	8	—	—	—	—	—	—
GFDL-Q	12	13	—	—	—	—	—
OSU	17	30	26	15	9	—	—
GFDL-R30	—	—	30	22	20	—	—
UKMO	—	—	35	24	2	—	—

[a] Joyce (1995).
[b] Nungesser et al. (1999).
[c] VEMAP (1995).
[d] Vasievich and Alig (1996).
[e] GISS refers to the scenario from the Goddard Institute for Space Science Mode, GFDL-1 and GFDL-Q refer to results from the Geophysical Dynamics Lab model, OSU refers to a climate model developed by Schlesinger et al. at Oregon State University, and UKMO refers to the United Kingdom Meterology Office model. All are described in Melillo et al. (1993) or VEMAP (1995).

models. NPP is defined as the difference between gross primary production and respiration, where respiration includes maintenance and construction respiration. The amount of available light, water and nitrogen, air temperature, and the atmospheric concentration of carbon dioxide all factor in the calculation of gross primary productivity (McGuire et al. 1992). The assumption was made that annual changes in NPP could be converted to a change in growth in the growth and yield model. Changes in NPP were available at a finer spatial scale than the growth and yield models, and this information was aggregated to the regional scale, associated with appropriate forest types, and used to modify timber yield. Changes in NPP response were computed as change in the NPP response from the baseline climate run (current climate). The relative increase or decrease in NPP was used to impose a change on the yield functions in the Assessment System.

14.4.2 Forest sector impacts as modeled by TEM–Timber Assessment Projection System

To represent the variability of the four climate scenarios, the ecological projections were grouped into three categories based on the delta (change in NPP) calculation: minimum, mean, and maximum. The mean delta, mean change in NPP that occurred between the current CO_2 and $2XCO_2$ (double current carbon dioxide) projection, was calculated as the average across the four climate scenarios for each of ecosystems in TEM (Table 14-2). The maximum change and the minimum change across all four climate scenarios were also calculated for each ecosystem. The TEM types were then matched to the FIA forest types in ATLAS within the timber supply regions.

The Assessment System models the temporal dynamics within the forest sector, thus it was important to develop a pathway for the temporal changes. Transient climate models would be available for the 2005 RPA Timber Assessment analysis, but for 1993 RPA Timber Assessment the ecological changes over the 1990–2065 period were assumed to occur in a linear fashion. This linear change in NPP for each forest type was used to modify the growth and yield functions in ATLAS over time.

The TEM-Timber Assessment Projection System projections were compared to the base Timber Assessment projection. The base projection can be considered to represent forest development under a continuation of current or historical climate because the ATLAS growth

Table 14-2. Comparison of the changes imposed on the ATLAS growth and yield functions in the 1993 and 2005 RPA Timber Assessments

Region	Forest type	1993 RPA Timber Assessment analysis			2005 RPA Timber Assessment analyses		
		Minimum delta	Mean delta	Maximum delta	Lower confidence interval	Delta	Upper confidence interval
		Percent change in growth rate					
Pacific Northwest East							
	Ponderosa pine	15	20	25	14	15	17
	True fir	17	22	24	12	15	17
	Lodgepole pine	14	21	24	13	15	17
Pacific Northwest West							
	Douglas fir	15	21	30	10	12	13
	Hemlock	17	22	30	10	11	13
	Fir–spruce	17	22	28	9	11	14
	Pine	10	18	25	10	12	14
	Softwood–mixed	14	18	20	4	10	16
	Red alder	15	21	30	10	12	13
	Hardwood–mixed	−0.4	10	27	9	14	18

Table 14-2. Continued

Region	Forest type	1993 RPA Timber Assessment analysis			2005 RPA Timber Assessment analyses		
		Minimum delta	Mean delta	Maximum delta	Lower confidence interval	Delta	Upper confidence interval
Pacific Southwest							
	True fir	14	20	27	15	17	20
	Redwood	10	13	20	12	14	17
	Hardwood	12	17	24	29	32	36
	Douglas-fir	8	12	22	12	14	17
	Ponderosa pine	10	16	21	16	18	20
	Mixed–conifer	14	20	27	14	16	19
Rocky Mountain North							
	Douglas fir	15	25	30	15	16	18
	Ponderosa pine	16	23	29	16	18	19
	Fir–spruce	21	34	42	11	13	14
Rocky Mountain South							
	Douglas fir	13	24	31	14	16	18
	Ponderosa Pine	13	18	23	13	15	17
	Fir–spruce	24	35	40	9	10	12
	Lodgepole pine	20	31	37	9	12	14
	Hardwood	21	32	37	22	28	34
North Central							
	White–Red–Jack pine	12	21	30	13	14	16

	Spruce–fir	25	29	36	26	26	27
	Swamp conifer	26	30	39	28	28	29
	Oak–hickory	6	17	34	21	22	23
	Lowland hardwoods	10	21	33	16	17	18
	Maple–birch	12	21	37	21	22	23
	Pine	10	19	27	16	17	18
Northeast							
	White–Red–Jack pine	12	21	30	12	13	14
	Spruce–fir	25	33	39	11	12	14
	Loblolly	10	14	18	16	18	20
	Oak–gum						
	Oak–pine	9	14	17	16	17	18
	Oak–hickory	4	17	36	20	21	22
	Elm–ash–red maple	13	24	39	14	17	20
	Maple–beech–birch	22	25	33	15	16	17
	Aspen	23	27	32	12	13	14

Table 14-2. Continued

Region	Forest type	1993 RPA Timber Assessment analysis			2005 RPA Timber Assessment analyses		
		Minimum delta	Mean delta	Maximum delta	Lower confidence interval	Delta	Upper confidence interval
South Central							
	Natural pine/planted pine	4	11	19	5	5	6
	Oak–pine	4	11	19	11	11	12
	Upland hardwoods	−4	11	33	21	21	22
	Lowland hardwoods	−4	14	31	12	12	13
Southeast							
	Planted pine	2	12	20	7	7	8
	Natural pine	2	13	20	7	7	8
	Oak–pine	2	12	20	14	15	16
	Upland hardwoods	−7	16	43	18	19	20
	Lowland hardwoods	−0.5	16	32	17	18	19

The changes from the 1993 RPA Timber Assessment were developed using changes in NPP over the projection period of 1991–2065. The changes from the 2005 Timber Assessment were developed using changes in vegetation biomass, and for this table, the same time periods are summarized.

and yield relationships are derived from either existing models or historical data collected from existing trees (Mills and Haynes 1995).

Because timber demand is national, shifts in the relative productive capacity between regions will affect timber supply. For the mean projection, while all regions showed an increase in productivity capacity, the southern regions showed the smallest increase to climate change. On a percentage basis, high elevation forests or those in the North experienced significant gains. Hardwoods in the South experienced the largest productivity fluctuations between the minimum and maximum scenarios.

With a change in available supplies of harvestable inventories, there is a rebalancing of harvest across the USA as the Assessment System model adjusts demand in various regions to take advantage of lower-cost raw materials. Balancing also takes place between softwood and hardwood fiber types, as well as between FI and NIPF ownerships (Mills and Haynes 1995). As supply of softwood growing stock increases and prices decline, the amount of hardwoods used in the harvest mix declines. This shift increases the demand for softwood pulpwood while reducing demand for hardwood pulpwood. Increased softwood timber supplies also act to increase softwood sawtimber capacity, and lower softwood lumber prices result in some increases in lumber production in the South (Mills and Haynes 1995).

Competition between major timber-producing regions results in harvest shifts. As harvest shifts between owners, it also shifts toward regions with established capacity and lower production costs. While all regions, except the North, gain harvest under each of the three scenarios, the North experiences slight losses under the minimum and maximum scenarios. Meanwhile, the harvest increase in the South is proportionally greater than that in the combined regions of the Northwest and Southwest Pacific. These harvest shifts contrast with the productivity response across the regions. The established capacity and lower production costs continue to favor the South, even though the productivity increases are greater in other regions of the country. These results also illustrate that simply having increased timber inventories does not necessarily translate to increased harvests, and that including the details of the market altered the impact of climate change (Joyce et al. 1995). Similarly, other studies, such as Binkley (1988) projected a large impact on the forest sector, focusing only on one large region. Expanding the study to include other forest regions

as well as the market details also altered the impact of climate change on the forest sector.

Some of the limitations of the first TEM–Timber Assessment Projection System application were changes in growth did not recognize potential differences in species productivity, as ecosystems, not individual species, were modeled. Nor were site characteristics, stand age, or forest management regimes a factor in determining the ecological response. The ecological model was an equilibrium model and did not consider the successional biogeochemical processes. Changes in forest productivity over time were assumed to be linear under climate change. This study did not account for climate-induced changes in Canadian inventories or that effect on Canadian exports to the US. Land-area changes were assumed to be similar across the baseline and the climate change scenarios.

Some of these limits have been addressed in the 2005 RPA Timber Assessment and in other studies. For example, land-area change is sensitive to climate-induced shifts in prices, as shown in the National Assessment Forest Sector analyses (NAST 2001). When stumpage prices drop more forest acres are likely to be converted to agriculture or, more likely, fewer agricultural acres will be converted to timberland (Irland et al. 2001).

14.5 PROJECTING CLIMATE CHANGE, ECOLOGICAL IMPACTS, AND FOREST SECTOR IMPACTS: THE TRANSIENT ANALYSIS IN THE 2005 RPA TIMBER ASSESSMENT

As the climate models and data-capture technology improved, the annual dynamics of climate throughout the projection periods became available. These “transient” scenarios provide the annual and monthly data on precipitation and temperature for use in ecological models such as TEM. In the 2005 RPA Timber Assessment (Haynes et al. 2007), transient climate scenarios were used to explore the potential impacts of climate change on forest productivity and the forest sector. A climate scenario from the Hadley Centre in the UK was used (NAST 2001). This scenario projected warming over the 21st century of approximately 3°C for the US. Regionally, a 2–3°C increase

was projected for the East and greater increases were projected for the West (see NAST 2001). Slight increases in precipitation, varying regionally, were also projected.

14.5.1 Ecological response

The influence of elevated atmospheric carbon dioxide on forest growth and ecosystem dynamics is an area of extensive experimental research (Ehleringer et al. 2005). Models with and without the influence of elevated carbon dioxide can show dramatically different results because of the influence of carbon dioxide fertilization or, in more arid regions, the water use efficiency effect. The current field research on the influence of elevated carbon dioxide on plant growth and biomass accumulation suggests that the "fertilization" effect may be less than originally thought. Thus, for the 2005 RPA Timber Assessment, two climate scenarios were explored: the climate and elevated carbon dioxide effect on vegetation; and only the climate change effects on vegetation. Previous analyses suggested that the scenario of only climate would show a less favorable future environment for ecosystem productivity (VEMAP 1995).

Following the changes made in assessing the ecological response to climate change in the National Assessment (NAST 2001), the information passed from the ecological model to the forest sector model was computed based on vegetation biomass (modeled as vegetation carbon) rather than changes in NPP. Vegetation biomass was a more synthetic response than NPP, in terms of ecosystem dynamics (Perez-Garcia et al. 2002).

A comparison of the ecological responses computed for similar forest types in the 1993 and the 2005 RPA Timber Assessments are shown in Table 14-2. For those forest types analyzed in both the 1993 and the 2005 analyses, 33 of the 48 types had a decrease in the relative response to climate change, on average, of 21%. This change in response reflects the shift to using the vegetation carbon as the basis for the delta (see Sect. 14.3.3) as well as the different climate scenario. The largest differences were in the northern and highest elevation forests. In some regions, such as the Pacific Southwest, the responses to climate change and carbon dioxide increased.

14.5.2 Results of TEM–Timber Assessment Projection System analyses

As expected, the forest growth and inventory response to projected climate and carbon dioxide change was greater than the climate-only scenario. This response results from the assumption that elevated carbon dioxide increases the water-use efficiency for some forest types and, in some cases, increases the nutrient response.

In the climate and carbon dioxide scenario, softwood and hardwood growth on private lands expand steadily (relative to the projection without any climate change), whereas in the climate-only scenario, only those regions with favorable climates increase in growth, such as the Southeast (Haynes et al. 2007). Reflecting these differences, the increase in national inventories is greater under the climate and carbon dioxide scenario than under the climate-only scenario (9.3% versus 2.3% for softwood inventories and 5.6% versus 1.2% for hardwoods) (Haynes et al. 2007). For softwood inventories, the greatest relative increase for both scenarios was in the South. In the baseline run without climate change, hardwood inventories declined throughout the projection period. Under the climate and carbon dioxide projection, hardwood growing stock rose steadily (Haynes et al. 2007).

Inventory changes across the regions are gradual, thus their impacts on private timber harvest, timber prices, and on product markets and prices are relatively small and extend over the projection period (Haynes et al. 2007). For example, total US softwood sawtimber harvest in 2050 increases by 0.9% in the climate and carbon dioxide scenario and by only 0.3% in the climate-only scenario. For the climate-only scenario, the small aggregate increase reflects the mix of harvest expansion in some regions (Pacific Northwest West, Pacific Southwest, and Southeast) and decline in others (Pacific Northwest East, Southern Rockies, North Central, and South Central). Regional stumpage prices are somewhat more sensitive, with 2050 softwood sawtimber prices falling by 18% in the Pacific Northwest West and 11% in the South under the climate and carbon dioxide scenario. In the climate only scenario, 2050 Pacific Northwest West prices fall by 6% and by 1% in the South.

Impacts in national product markets are further muted by extensive interregional and international substitution (Haynes et al. 2007). By 2050 annual softwood lumber production in the USA rises by about 1.1% in the climate and carbon dioxide scenario, imports fall by 1.1%,

and consumption rises by about 0.2%. National market changes for the climate-only scenario are half or less than with climate and carbon dioxide scenario.

14.6 FOREST SECTOR MARKET MODELS WITH INTERTEMPORAL OPTIMIZATION

Chapter 2 classified forest sector market models by the number of market levels (multiple versus single), treatment of spatial relations, and assumptions about future knowledge of market agents. The two sets of assumptions about market agents are limited knowledge (static/myopic) and perfect knowledge (dynamic/intertemporal optimization). All of the analyses discussed to this point have examined climate change impacts on forest sectors as modeled using multiple levels of markets, spatial relationships treated, and limited knowledge. Forest sector models using intertemporal optimization also have been used to explore the impact of climate change on forestry; one example is described in Section 14.6.1.

14.6.1 FASOM

FASOM is a multiperiod, nonlinear, price-endogenous, mathematical intertemporal optimization programming, economic model that provides 100-year projections of forest sector production, prices, and welfare (McCarl et al. 2000). This model has been used to explore the impact of climate change on the forest sector. Similar to the approaches above, a projection of the impact of climate change on forest productivity is used to set the context for the climate change impact on the forest sector. For example, Burton et al. (1998) assumed changes in annual growth (no links to ecological models), whereas Irland et al. (2001) used the ecological models (TEM, CENTURY) (NAST 2001) to modify growth and volume in FASOM.

Irland et al. (2001) explored the impact of four scenarios (two climate scenarios and two ecological models) on the forest sector. The two climate scenarios were the Hadley scenario (described in Sect. 14.5) and the Canadian scenario. The Canadian scenario projected a warming of 5°C for the USA over the next 100 years, a warmer projection than the Hadley (NAST 2001). Decadal vegetation carbon changes were used to adjust the forest growth in FASOM. Analyses

of these particular scenarios indicate that timber inventories increase over the next 100 years. This increased wood supply results in reduced log prices, which, in turn, decrease timber producers' profits (Joyce et al. 2001). At the same time, lower forest product prices mean that consumers generally benefit. The net effect on economic welfare of participants in both timber and agricultural markets was projected to increase in all scenarios from 0.4% to 0.7% above current values. Although total forest production increases, hardwood output is higher in all scenarios whereas softwood output increases only under moderate warming. Increased forest growth translates into higher forest production, as represented by the harvest levels. By 2100, inventories are slightly higher for the climate change scenarios, compared with the base where no climate change is assumed. As in previous analyses, increased forest growth leads to increased log supply, reductions in prices, and timber producer welfare (profits) declines whereas consumer welfare (prices) increases.

In contrast to the 2005 RPA Timber Assessment analyses above, FASOM examines land-use shifts between agriculture and forestry as these economic sectors adjust to climate-induced changes in production. In these scenarios, the shifts between forestry and agriculture varied by the climate scenario considered; land-use shifts were more favorable for forestry under the Canadian scenario versus the Hadley (Irland et al. 2001).

Although previous studies and this analysis differ in the degree of market and human adaptation, a general conclusion is that timber and wood product markets will likely be able to adjust and adapt to climate change (Irland et al. 2001). Assumptions about changes in population, land use, trade in wood products, consumption of wood products, recreation patterns, and human values are highly uncertain on a century timescale, and are likely to be major factors that determine socioeconomic impacts on the USA (NAST 2001).

14.6.2 Ecological models incorporating species distributional shifts

In the 2005 RPA analyses, the impact of climate change influences only the growth of trees in the future scenarios. Disturbances such as fire or beetle outbreaks are assumed to occur at the historical levels and impact the timber inventory in historical patterns. The potential

for large areas of trees to suffer extensive tree mortality (dieback associated with stress, beetle outbreaks, or large fires) is not considered, nor is the potential for salvage considered. The large catastrophic events potentially may shift species composition, change the forested landscape quickly (Dale et al. 2001), and potentially alter the supply of timber for short periods. The near-term impacts on the market in terms of supply as well as the potential management options for replanting are important consequences of such large-scale dieback. Producer options are limited in the ecological models—although management intensification can occur, genetic stock improved for climate change or tree species cannot be changed. Further the migration of species to a more favorable climate was not incorporated in those analyses.

14.6.3 Analysis of large-scale forest diebacks and the forest sector response

Large-scale changes in the distribution of forests and extensive mortality events have been suggested in different ecological analyses (VEMAP 1995; Dale et al. 2001). These events have the potential to alter the availability of timber in a short period. Sohngen and Mendelsohn (1998) developed a national model of the stumpage market of four timber types (loblolly pine, white pine, Douglas-fir, and ponderosa pine) that focused on the dynamic adjustment of the market to large-scale catastrophic events, such as extensive dieback associated with climate change.

Steady-state analyses of the ecological response to climate change by VEMAP members (1995) were converted to dynamic responses by assuming a linear pathway for climate change. The magnitude of the biome shifts in the VEMAP scenarios can be seen in the metric computed by Sohngen and Mendelsohn (1998). A shifting proportion is that proportion of the initial steady-state forest area that shifts out of one particular forest type and into a different type. For loblolly pine forests, for example, little change occurs under the OSU climate scenario with both the Dynamic Global Phytogeography Model (DOLY) and the BIOME2[2] model, whereas large-scale shifts occur for ponderosa pine forests under both the United Kingdom Meteorological Office (UKMO) and OSU climate scenarios with the DOLY

[2] BIOME is a word (not an acronym)—biome, describing a well-defined biological community (grassland, etc.).

model and the BIOME2 model. Productivity shifts over the projection period ranged from increases for all forest species modeled with the TEM model to declines in productivity of nearly all forest types modeled with the Biome Biogeochemistry Model (BIOME-BGC) under the UKMO climate scenario.

In order to incorporate a management response to the climate-induced diebacks, two dynamic ecosystem pathways were developed: (1) dieback, where all trees from the previous forest type are assumed to die in the decade of the shift and natural regeneration proceeds very slowly and (2) regeneration, where the shifts do not result in extensive mortality but affect the speed of the regeneration (options to plant new species adapted to the new climate or to allow natural adaptation where successional forces result in new species over a longer period). In Table 14-3, a combination of 36 scenarios are shown where the climate model (UKMO, OSU) is varied with the biogeographical model (DOLY, BIOME2, MAPSS) and the biogeochemistry model (TEM, CENTURY, BIOME-BGC) and all under two ecosystem pathways over the planning period. The pathways include a dieback scenario where disturbance results in large-scale tree mortality and slow successional changes returning to forest, and regeneration where after the large-scale mortality event, trees adapted to the new climate are planted.

The analysis includes two management intensity levels associated with land ownership behavior. Intensively managed lands such as plantations are more likely to be associated with management to maximize the present value of timber net income and to plant species that are adapted to the new climate. Less-intensively managed lands are assumed to rely on natural succession for regeneration, and under the climate change scenario, this option results in a longer time for species adapted to the new climate to regenerate the site.

For both ecosystem pathways (dieback and regeneration), the results indicate a welfare gain across all of the climate scenarios; timber supply expands and prices are reduced below a baseline (no climate change) (Table 14-3). Sohngen and Mendelsohn (1998) indicate that the nearly similar values in welfare for the dieback pathway and the regeneration pathway are the results of three factors: (1) the most vulnerable regions, such as the North and Rocky Mountains, have primarily low-valued species; (2) harvests remove trees prior to mortality and through salvage; and (3) planting species better suited to be in the new conditions allows the vulnerable forest to adapt quickly.

Table 14-3. Change in the net present value of new market surplus in timber markets for climate change cases relative to the baseline (from Sohngen and Mendelsohn 1998)

Ecosystem pathway and climate models	Biogeographical models					
	DOLY		BIOME2		MAPSS	
	Billions 1982$	*Percent change*	*Billions 1982$*	*Percent change*	*Billions 1982$*	*Percent change*
A. Dieback						
	TEM (Biogeochemistry model)					
UKMO	30.05	10.62	27.52	9.71	19.10	6.74
OSU	28.94	10.21	30.16	10.64	31.77	11.21
	CENTURY (Biogeochemistry model)					
UKMO	18.87	6.65	17.89	6.31	9.46	3.34
OSU	14.23	5.02	16.69	5.89	17.80	6.28
	BIOME-BGC (Biogeochemistry model)					
UKMO	9.35	3.30	10.31	3.64	2.63	0.93
OSU	11.86	4.19	13.72	4.84	14.52	5.12
B. Regeneration						
	TEM (Biogeochemistry model)					
UKMO	31.20	11.01	32.58	11.50	22.62	7.98
OSU	31.93	11.27	33.16	11.70	35.26	12.44
	CENTURY (Biogeochemistry model)					
UKMO	20.47	7.22	22.99	8.11	11.03	3.89
OSU	17.11	6.04	20.34	7.18	21.92	7.74
	BIOME-BGC (Biogeochemistry model)					
UKMO	10.37	3.66	14.98	5.29	3.87	1.37
OSU	15.06	5.31	18.01	6.36	16.72	5.90

Net present value is measured with a discount rate of 5%.

To compare these transient results for welfare with a steady-state situation, they computed the predicted change in welfare under the steady state. For MAPSS and BIOME-BGC projections, the welfare would be −\$25.1 billion and +\$73.6 billion for the DOLY and TEM combination, whereas the dynamic model computations are +\$2.63 billion and +\$31.2 billion, leading to their conclusion that the steady-state responses overstate the welfare effect. This study of Sohngren and Mendelsohn (1998) was the first to carefully incorporate management responses to extensive mortality events from climate change and suggest the forest sector is adaptive to such changes.

14.7 GLOBAL TRADE AND CLIMATE CHANGE IMPACTS

Building on the methods used to assess the US forest sector, Perez-Garcia et al. (1997) analyzed the impact of climate change on forest productivity and on forest products consumption, prices, and trade. Productivity changes for 18 vegetation types were simulated with the TEM model at the 0.5 degree latitude by 0.5 degree longitude scale under four different climate scenarios (Melillo et al. 1993). NPP was the ecological variable used to develop the impact of climate change on the growth and yield functions in the global trade model. The University of Washington CGTM computes market equilibria for regional forest product sectors considering constraints on processing capacity and available wood resources (Perez-Garcia et al. 1997). CGTM divides the globe into 43 log-producing regions and 33 product-consuming regions, simulating over 400 trade flows.

Because infrastructure, rather than forest growth rates, constrained timber supply at the time in a few of the larger regions, two economic scenarios were explored. The intensive margin scenario constrains harvest to the reference case (no climate change) in all regions where the log supply has a fixed upper limit, such as the maximum allowable annual cut. China, an exception to this scenario, was a net importer of wood products at the time of the analysis; higher growth rates would be expected to translate directly into higher levels of domestic production. The extensive margin scenario assumes that changes in growth rates would lead to changes in harvest in all of the supply regions with a fixed upper limit as well as all regions where timber supply is a function of log price.

Across the four climate scenarios, NPP generally increases, resulting in more abundant timber, falling prices and increases in consumption. Consistent across all climate scenarios and the two economic scenarios, consumers of forest products benefit, whereas the impact on timber producers is mixed, but negative as prices fall more than output expands.

Regional differences in the climate change impact results in regional differences in economic impact (Perez-Garcia et al. 1997). In the intensive margin scenario, forest sector activity increases but generally less than the increase in NPP. Nearly all of the domestic gains in softwood productivity associated with more favorable climates are captured by Canada, China, and other consumer countries in Asia. For example, NPP increases in Canada range from 15% to 22% and softwood log production increases by 13–22% (depending on the climate scenario). In contrast, NPP in the USA increases by 13–17%, whereas the log supply increases are less than 8%. In Finland and Sweden, log supply declines by 4–10%, even through softwood growth was projected to increase by 18–32%. For hardwoods the results are similar but with different regions benefiting.

At the time of the analysis by Perez-Garcia et al. (1997), the future development of the former Soviet Union with respect to forestry was uncertain. Two-thirds of the global softwood inventory is in the former Soviet Union. In the extensive margin analysis, production from the former Soviet Union substitutes for Canadian production. Output gains from the favorable climate in the US and in Europe also suffer.

The four GCMs produce surprisingly consistent economic results, with expanding NPP of the world's forests generally hurting timber-producing regions and benefiting consumers. The overall net economic impact is positive, with the net present value (computed with a 4% real discount rate) of the benefits to the forest sector ranging from $10.7 billion to $15.9 billion (1980 US$), depending on the choice of GCM and economic scenario. This result is positive but lower than the range previously reported for an analysis of the impact on the world's boreal forests (Binkley 1988). Perez-Garcia et al. (1997) conclude that including more of the possible economic adjustments reduced the measured impact of climate change, and that without these additional details, the impact was overstated.

The NPP results across the four different GCMs produced relatively minor differences in the forest products markets, because trade tends to dampen the effects (Perez-Garcia et al. 1997). In contrast, the

different assumptions about timber supply in comparatively undeveloped regions produced variation in economic outcome of comparable magnitude to the differences among GCMs. Perez-Garcia et al. (1997) conclude that it appears to be at least as important to have a more precise understanding of economic and institutional response to climatic change as it is to improve the understanding of the biophysical responses. Uncertainty in the economic models appears to be at least as great as the uncertainty in the GCMs.

14.7.1 Global trade and shifts in vegetation carbon

With different climate scenarios and different assumptions about the ecological impacts, the CGTM was used in a second analysis of the impacts of climate change on the global forest sector (Perez-Garcia et al. 2002). Three transient climate change scenarios for the period 1990–2100 were taken from the integrated global system model (IGSM) sensitivity study (Prinn et al. 1999) where a range of uncertainty in parameters was used to generate low and high levels of greenhouse gas emissions with no implementation of emission control policies. Global annual mean temperature in 2100 increases over the 1990 value about 2.6°C for the midrange scenario, 3.1°C for the high emission scenario, and 1.6°C for the low emission scenario. The TEM model is run in a transient mode, producing vegetation carbon dynamics annually throughout the period. In this application, TEM simulated the dynamics of potential mature natural vegetation, and the metric of change was the response of vegetation carbon to climate change. This response was imposed across all age classes in CGTM.

Across the three climate scenarios, the TEM results are most similar between the midrange and the higher emission scenarios, and the greatest regional differences appear between the lower emission scenario and the midrange scenario. By the end of the analysis period (2040), the potential response in regional forest growing stock ranges from decreases to increases for the low emission scenario to increases in all regions for the high emission climate scenario. Globally and under all scenarios, higher growth leads to larger timber growing stock that lowers log prices, increases consumption, and improves total economic welfare. While the global price changes (from −0.8% to −3%) and harvest changes (1.5–2.7%) are small and probably within uncertainties of the CGTM projections, the regional results vary considerably among themselves and with the global results, reflecting the importance of

trade in forest products (Perez-Garcia et al. 2002). Regionally, price declines range from near zero (Canada) to more than 7% (Scandinavian region), depending on the climate and economic scenario.

Regional responses in welfare are positive for some and negative for others depending on the scenario (Table 14-4). Across the regions, the welfare responses by group (timber owners, mill processors, and product consumers) are affected differently. Markets and trade in forest products play important roles in whether a region realizes any gains associated with climate change. In general, regions with the lowest wood fiber production cost are able to expand harvests. Trade in forest products leads to lower prices elsewhere. The low-cost regions expand market shares and force higher-cost regions to decrease their harvests. Trade produces different economic gains and losses across world regions although, globally, economic welfare increases.

Table 14-4. Aggregate price change, harvest change, and total economic welfare, defined as the sum of economic welfare to the timber producer, log processor, and product consumer for major forest sector markets (the USA, Canada, Chile, New Zealand, western continental Europe, Finland, Sweden, and Japan) (Perez-Garcia et al. 2002)

Scenario and type of change	Intensive margin	Extensive margin
	Percent	
High emission climate scenario		
Price change	−2.91	−3.09
Harvest change	2.73	2.45
Total welfare change	0.41	0.44
Total welfare change (1993$)	(15 billion)	(15.8 billion)
Moderate emission climate scenario		
Price change	−2.30	−2.44
Harvest change	2.36	2.20
Total welfare change	0.32	0.32
Total welfare change (1993$)	(11.6 billion)	(11.6 billion)
Low emission climate scenario		
Price change	−0.83	0.86
Harvest change	1.49	1.49
Total welfare change	0.11	0.04
Total welfare change (1993$)	(3.9 billion)	(1.8 billion)

Changes are measured from the economic baseline (no climate change) and include both softwood and hardwood changes. Total welfare changes are measured as the cumulative annual net present value discounted at 5% and expressed in 1993 US$.

The results of this second study by Perez-Garcia et al. (2002) indicate that assumptions within alternative climate scenarios and about trade in forest products are important factors that strongly influence the estimated effects of climate change on the global forest sector.

14.7.2 Future price insight and climate change responses in the forest sector

Sohngen et al. (2001) developed a forest sector model by using intertemporal optimization that explored the impact of climate change on the global forestry sector. The economic model incorporates 46 different ecosystem and management types throughout the world, ranging from heavily managed subtropical plantations, to unmanaged inaccessible forests in tropical and boreal zones. Steady-state results from the ecological model, BIOME3 (Hazeltine and Prentice 1996) and two climate scenarios are converted into transient scenarios making the assumption that changes in ecosystems occur proportionally to the changes in climatic variables. The ecosystem pathways of dieback and regeneration are developed following Sohngen and Mendelsohn (1998). Future price expectations optimally adjust timber investments and rotation age in the dynamic optimization models (Sohngen et al. 2001).

All prices are predicted to be lower with higher timber harvests under climate change. In the dieback scenarios, prices are higher than in the regeneration scenario as dieback contributes a large proportion of timber supply in the near term. While forest area expands 22–29%, most of this expansion occurs in less productive regions and in regions that are relatively less accessible (Sohngen et al. 2001). With the reduction in timber prices, these regions remain unlikely to be harvested. One exception is the former Soviet Union where gains in forest productivity are particularly large. Plantations expand slightly in emerging subtropical regions, taking advantage of not only higher yield but also with short rotations (10–20 years); they can also exploit the near-term dieback in the temperate forests.

Globally, net market surplus is expected to increase 3–6.7% of the total value of the market, slightly greater results than Perez-Garcia et al. (2002). The regional results vary from the global. North American and the former Soviet Union see welfare losses, as a result of

dieback. Consumers and producers gain from climate change in developing countries through lower prices and minimal dieback with higher forest productivity.

Conclusions in this analysis about the importance of the temporal dynamics by Sohngen et al. (2001) are similar to those found by Perez-Garcia et al. (2002). Additionally, this study was the first to contribute to a global assessment of the consequences of large mortality events and the forest sector response.

14.8 CLIMATE SCENARIOS AND ECOLOGICAL MODELS: FUTURE DIRECTIONS

The dynamics of global and regional climate are influenced by the energy and chemistry of the Earth's atmosphere and the ocean dynamics. Carbon dioxide, methane, nitrous oxides, chlorofluorocarbons, and water vapor, known collectively as greenhouse gases, have the potential to warm the atmosphere. The amount of warming is a function of the ability of these gases to absorb solar radiation (a physical constant) and the atmospheric concentration of each gas. For carbon dioxide, methane, nitrous oxides, and the chlorofluorocarbons, their concentrations since preindustrial times have increased from 13% (nitrogen oxides) to 145% (methane). Approximately three-quarters of the carbon dioxide emissions are from fossil-fuel combustion, the rest from land-use change (IPCC 2001). Increasingly, the relationship between human-caused greenhouse gas emissions and a warming climate is being documented (US CCSP 2004; IPCC 2007).

General or global circulation models are used to study the dynamics of the atmosphere, the natural variability in climate (Earth's orbit, solar activity), and its interactions with the Earth's land surface and the ocean. These models have continued to evolve over time as atmospheric scientists continue to learn more about the role of clouds, interactions with the land surface and the ocean, and the chemistry of the atmosphere. Land-surface processes such as land-use change and vegetation cover are represented simplistically in these climate models. The IGSM project brought together the atmospheric models and most detailed land-surface models to study the interaction between climate changes and land-surface processes such as vegetation change and productivity shifts (Prinn et al. 1999). Such models may one day allow

for detailed policy analysis of land management policy actions, carbon accounting, and climate change thresholds.

Like the spectrum of forestry models discussed above, the current atmospheric models contain a similar set of physical and chemical processes, but may express the mathematics of these processes slightly differently. Thus, there is value in using more than one climate model or more than one model run associated with each climate model in any analysis of the impacts of climate change on forest productivity and the forest sector. Adopting a spectrum of projections helps address the uncertainty of future climate projections and associated ecological impacts of climate change.

The spatial resolution of these current models is much larger than the spatial scale of forest management or of current ecological models. The results of these models must be scaled down to the appropriate levels for use in ecological models, and these downscaling methods vary, resulting in different realizations of future climate at the regional scale. Technological improvements are bringing near the time when these climate models can be used at regional or subregional scales to explore climate patterns over time.

Because greenhouse gases are a forcing factor in climate, and concentrations of these gases, such as carbon dioxide, could conceivably double or triple over the next 100 years, projections of future climate must include assumptions about future trends in emissions of these greenhouse gases. Greenhouse gas concentrations are influenced by economic activity, population growth, and demand for energy resources. As a part of the climate change analyses associated with the IPCC, a series of emission scenarios is developed and these scenarios, provided to numerous climate modelers, are used to develop climate scenarios that then become available to other scientists interested in modeling the impact of climate change on ecological and economic processes. General economic assumptions in global analyses of the forest sector may need to be more consistent with the economic assumptions associated with the climate scenario and the underlying emissions scenarios.

The evolution of these climate models has allowed increased temporal detail for the ecological analysis of the impact of climate change on forest productivity and the forest sector. The earlier static analyses of climate change impacts on the forest sector have been replaced with analyses using a transient scenario. All but the Irland et al. (2001) analysis and the 2005 RPA Timber Assessment analysis (Haynes et al.

2007) are based on extending the steady-state analysis through assumptions about how the steady-state analysis could be implemented over time. Irland et al. (2001) and Haynes et al. (2007) used the ecological responses annually to develop a 5-year or decadal change for the growth and yield functions. The 2005 RPA Timber Assessment went further to develop differential responses by age class. All studies have shown the importance of addressing the temporal changes, either in the ecological response to climate or in the changes in timber inventory as a result of large-scale disturbances.

14.8.1 Ecological effects of climate change on forests

Sohngen and Sedjo (2005) described the influence of climate change on forest sector models as those influences affecting the stock (inventory) and the flow (growth). Early analyses, such as Joyce et al. (1995), focused on the flow effects, that is, how climate change altered forest growth. Later analyses, such as Sohngen and Sedjo (2001) demonstrated the importance of including the climate change effects on the stock—the potential for sudden and large shifts in timber inventory.

A wide variety of models have been employed to look at the impacts of climate change on forests and trees: biochemical and biophysical, whole-tree, gap-phase dynamics, forest biogeochemistry, and global vegetation models. All of these models are informed to some extent by experimental results, and continued model improvement will come with a closer communication between those conducting the experiments and those building the models (Norby et al. 2005).

For the analyses examining the impact of climate change on forest growth, a number of assumptions were made that could be further explored with the current sets of dynamic vegetation models (hybrids of biogeochemical and biogeographic models). Most of the analyses assumed that the impact of climate change on forest growth was the same across the age classes and site conditions. Additionally, while plantations were often included in the analyses, the impact of climate change was assumed to be the same for plantations as for the natural forests because most ecological models used in these analyses do not currently address plantations as a vegetation type. Management intensification options differed for plantations, such as the regeneration options in Sohngen and Mendelsohn (1998), but the climate responses were assumed to be the same as native vegetation.

The influence of carbon dioxide on forest growth and ecosystem dynamics is an area of extensive field research. Models with and without the influence of elevated carbon dioxide can show dramatically different results, the influence of carbon dioxide fertilization or in more arid regions, the water-use efficiency effect. This is an area that needs further clarification by ecologists.

For those analyses examining the impact of climate change on inventory shifts, factors influencing forest succession such as disturbances and how they are likely to change in the future have been included exogenously in the forest sector models. Here, the ecological models identify large-scale disturbances such as catastrophic fires or droughts. A pathway of response is developed exogenous to the ecological and the economic model. This pathway of response identifies the species response to climate change over time—the distributional shifts in forest types. Improvements in the modeling of forest successional process and the influence of vegetation management on the forest response would better describe the regeneration pathway under climate change. Large-scale dieback events alter the landscape in a short period of time and the successional response is likely to be highly unstable as species respond individually to the changing climate.

Perhaps the most challenging process to model is the migration of new species across the landscape. While this transient response has been modeled by many, the temporal dynamics of these migrations are highly uncertain, challenging the depiction of forest succession, natural regeneration, and the adaptation of new species in future projections (Iverson et al. 2004). These limitations restrict the application of these models for management recommendations on planting of new species.

14.8.2 Land-use modeling and climate change

This chapter focused on climate change impacts on forest sector models, and by focusing on a single sector, the potential for climate change to affect other sectors directly and the forest sector indirectly was not reviewed extensively. The FASOM analyses incorporated the opportunity to look at land-use change between agriculture and forestry as affected by climate change. Results indicate that price shifts under climate change can influence the management response on land use—converting agricultural land to forestry or vice versa. The potential for land-use shifts related to urbanization may be another factor of

concern in the forest sector dynamics. This land-use change is likely to affect areas currently impacted by urban expansion into rural communities. Population growth may increase in locations where climate is likely to remain more favorable, for example, mountain communities versus lower-elevation communities or urban areas in the South.

14.8.3 Incorporating uncertainty into the analyses

As discussed earlier, there is great uncertainty in future climate projections which leads to uncertainty in both ecological and economic impacts of climate change. Improving climate models by themselves will not resolve many of the uncertainties surrounding the climate issue. Instead we will need to understand the conditions that bound the range of uncertainty, including the relevant uncertainties of managing forests and evolving market conditions.

The IPCC (2001) describes managing uncertainty as "taking account of uncertainty and appropriately integrating it into policy and decision-making processes." They identified two approaches:

> One strategy is to consider decision approaches that are robust against the complex and deep uncertainties associated with climate change. The focus here is to seek strategies that are relatively insensitive to uncertainty about future climate change. A second approach aims to improve decision-makers' capacity to handle risk about climate change by advocating a decision framework that explicitly considers all relevant uncertainties, including uncertainties not only in future climate but also its impacts. A refinement of this is an impacts threshold exceedance approach to climate change risk assessment in which thresholds of acceptable damage or loss are established which define the coping range of the system. Adaptation strategies are then evaluated according to their effectiveness at maintaining the level of damage at or within the acceptable thresholds or coping range.

One approach that can be used to seek the bounds of the uncertainty across both ecological and forest sector models is scenario planning. As argued elsewhere (see Chap. 2) scenario planning, as illustrated in this chapter, enables a discussion about differences in selected indicators of system performance. Differences in scenarios could be attributed to different approaches to managing sources of uncertainties. For example the results shown in Table 14-3 inform a discussion of the economic impacts of different climate models each with its underlying uncertainties. Such information helps policy-makers weigh the impacts associated with climate change with other risks that they are attempting to manage.

14.9 CONCLUSIONS

Climate change has been addressed in forest sector models using state-of-the-art ecological models to describe the influence of climate change on forest growth and sudden changes in inventory such as dieback. These analyses have shifted from steady-state or static analyses to incorporating the temporal dynamics of the climate change influence and the market responses. These bioeconomic analyses have expanded to include all forest types within a region to global analyses of the forest sector. Both the perfect foresight models and the timber supply models have been entrained into the analysis of climate change. The analyses have identified the importance of the temporal dynamics of the climate change effect, the influence of trade at the global scale, and the importance of identifying the regional response where management decisions will be made. Most critically, all of these analyses have stressed the importance of evaluating the ecological and the economic response in an integrated fashion. Taken in isolation, the ecological results overstate the impact of climate change on the forest sector.

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